Report

Paleofloods: changes in prehistoric flood occurrence

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2. Paleofloods: changes in prehistoric flood occurrence

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2.1. Introduction

Recurrence times of the most extreme events as well as periodicity of climate fluctuations usually exceed the time span of instrumental and historic records, so that knowledge of paleofloods is required to obtain a complete understanding of flood frequency and related controlling factors. Paleofloods are past or ancient floods that occurred without direct observation or recording by humans (BAKER 2006). Paleoflood records can be established by geologic (lake sediments, floodplains, geomorphology) or biologic (dendrogeomorphology, lichenometry) archives. These data can be merged with historic and instrumental data to obtain a complete past record of floods, also on younger timescales, and to calibrate the geologic/biologic archives. In this section, we focus on floods in Switzerland on a Holocene timescale and their analysis by means of paleoflood data, techniques and archive integration (SCHULTE et al. 2019a; 2019b; WILHELM et al. 2019).

The systematic records of streamflow from the Swiss urban areas in the lowlands go back to the early 19th century (e.g. the Basel–Rhine station, in operation since AD 1808). In the Alps, in contrast, instrumental hydrological measurements only go back 100 years and many of the time series are affected by flood gaps, e.g. from AD 1937 to 1967 (GEES 1997). For this reason, it is difficult to confidently assess floods with a return period of >200 years using short instrumental series (SCHULTE et al. 2015). The incorporation of paleoflood datasets into conventional flood-frequency analyses greatly extends the hydrological data series (COSTA and BAKER, 1981) reducing uncertainty (RUIZ-VILLANUEVA et al. 2013) and improving the data available for risk analysis (BAKER 2006; 2008). This approach is thus of great value for the planning of large-scale hydrological projects (e.g. OSTENAA and LEVISH 1996). Paleoflood data also provide a significant added value to the instrumental time series by defining the maximum limit of flooding in the analysis of envelope curves (ENZEL et al. 1993), or testing the analysis performed in the calculation of the probable maximum flood PMF (BENITO and THORNDYCRAFT 2005). The PMF has been used as a standard for hydrological analyses of dam safety, a critical topic in Switzerland, for decades. In Switzerland, dam safety guidelines prescribe the estimation of the so-called design flood with return period 1000 years, HQ1000, and the safety flood, estimated by 1.5·HQ1000 or the PMF for dam design (SFOE, 2008). Recent research has focused on using the PMF estimation based on hydrological modelling (ZEIMETZ et al. 2014; 2015), however, the use of paleoflood data series could also improve the estimation of HQ1000. A recent example in Switzerland is the EXAR project (Hazard information for extreme flood events on the rivers Aare and Rhine), which aims to acquire information on extreme floods with return periods between 10^3 and 10^7 years in the Aare and Rhine Rivers with paleoflood techniques. Also, the international FWG-INT project developed in the Bernese Alps is an innovative approach that integrates multi-archive datasets from floodplains, lakes, historical sources and botanical evidence for the development of a temporal-spatial (4-D) paleoflood model of alpine catchments (SCHULTE et al., 2019b).

Paleoflood studies do not necessarily provide analogues of future flood–climate episodes but they may provide evidence of flood response to climate shifts in terms of flood magnitude and frequency (KNOX 2000; REDMOND et al. 2002). Several paleoflood studies in Switzerland have documented the sensitivity of floods to climatic conditions and solar activity (SCHULTE et al. 2008; 2015; GLUR et al. 2013; WIRTH et al. 2013a, 2013b) and the preferential clustering of large floods in certain time periods, influenced by long-term trends in atmospheric circulation or oceanic sea-surface temperatures (SCHULTE et al. 2015; PEÑA et al. 2015).

2.2. Lakes as recorders of past flood events

Lakes act as efficient traps for clastic material eroded from the catchment slopes and floodplains and subsequently transported through the fluvial system (OLDFIELD 2000; SCHILLEREFF et al. 2014). Therefore, lacustrine sediments may record flood events in a continuous and high-resolution mode and thus provide an excellent archive for reconstructing past flood occurrence (e.g. NOREN et al. 2002; MORENO et al. 2008; DEBRET et al. 2010; GIGUET-COVEX et al. 2011; STØREN et al. 2012; WILHELM et al. 2012; CZYMZIK et al. 2013; GILLI et al. 2013; GLUR et al. 2013; WIRTH et al. 2013a). An important advantage is that lake sediments are barely prone to erosion (GILLI et al. 2013) when compared to much more erosive systems in fluvial sedimentary sequences (e.g. SHEFFER et al. 2003; MACKLIN et al. 2005; THORNDYCRAFT et al. 2005; SCHULTE et al., 2019). The intercalation of continuously deposited background sediment with discrete flood layers, usually differing strongly in lithology (**Box 2.1**), offers the potential for the reconstruction of a temporally complete flood record (GILLI et al. 2013). The temporal resolution of such lake-sediment sequences depends on the background sedimentation rate but in the case of annually-layered lithology (varves), even the seasons of paleofloods can sometimes be determined (WIRTH et al. 2013a). These lake-sediment sequences usually contain abundant terrestrial organic matter so that reliable radiocarbon dating can be established.

Extreme precipitation mobilizes and entrains large amounts of sediment particles in a catchment and feeds them into the river network. In the next downstream lake, these floods produce characteristic turbidite layers (MULDER and CHAPRON 2011; GILLI et al. 2013: SCHILLEREFF et al. 2014). Best-suited lakes for flood reconstructions have sufficient relief in the catchment, have inflows forming deltas, and are characterized by a flat and horizontal basin floor, where the flood turbidites accumulate and consequently level out inherited topography (GILLI et al. 2013). Single-lake records may be strongly influenced by local signals or particularities of the specific catchment, such as anthropogenic impact, glacier-cover change, or hydrologic changes. Regionally more significant paleoclimate reconstructions can be obtained using multiple-lake records through investigating and averaging as many sites as possible (see two case studies in sections 2.2.1 and 2.2.2).

Box 2.1: Lacustrine flood layers

Flood layers show a characteristic particle-size grading reflecting the waxing (i.e. coarsening up) and waning (i.e. fining) of the paleoflood hydrograph (**Figure**) (MULDER et al. 2003; LAMB and MOHRIG 2009; MULDER and CHAPRON 2011; GILLI et al. 2013). The top part of the flood layer shows the finest particles and has often a distinctive light colour. Sometimes, several stacked graded intervals within the same flood layer indicate multiple discharge peaks (GILLI et al. 2013). Similar turbiditic deposits may originate from subaquatic mass movements triggered by earthquake-induced shaking, delta overloading, or lake-level fluctuations (e.g. GIRARDCLOS et al. 2007; STRASSER et al. 2007; WIRTH et al. 2011). Hence, it is important to distinguish between flood- and mass-movement-induced turbidite layers (BECK 2009; WIRTH et al. 2011; SIMONNEAU et al. 2013). Mass-movement turbidites are composed by remobilized lake sediments showing a different grain-size pattern and mineralogical and organic composition than flood turbidites. They are often, but not necessarily, thicker than flood layers with a weaker grain-size sorting and a higher content of endogenic minerals and a dominance of aquatic organic material (ARNAUD et al. 2002; SIMONNEAU et al. 2013).

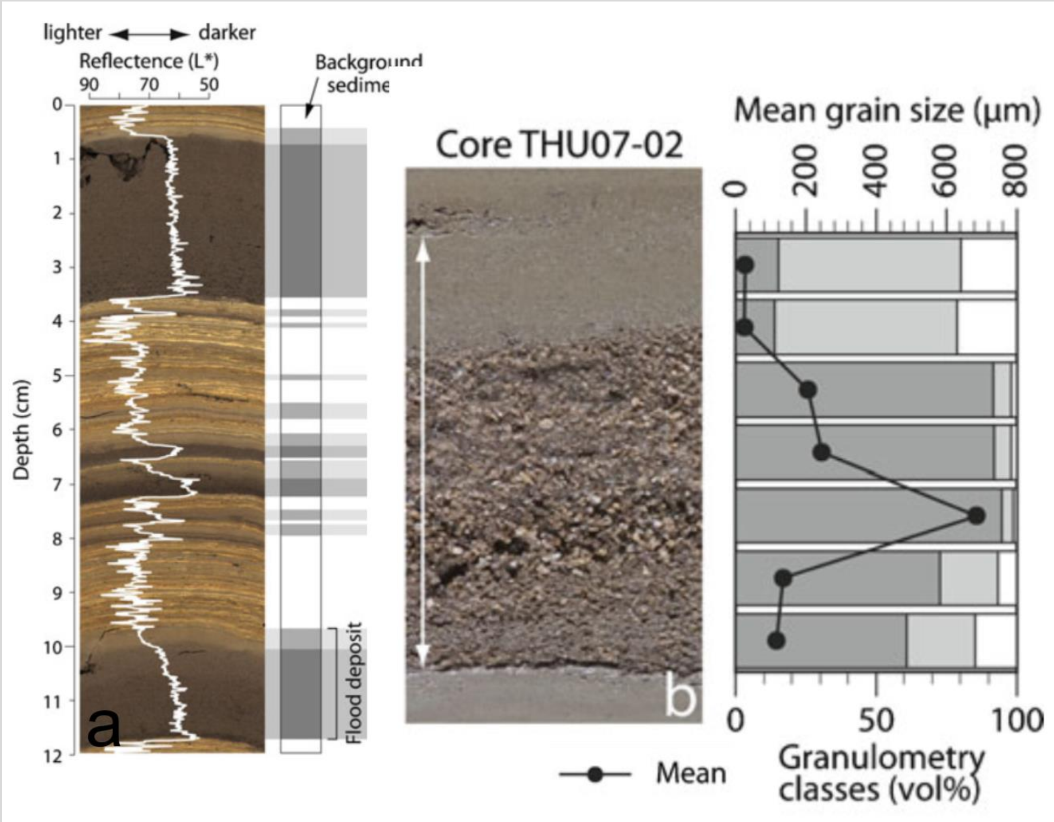

Figure: (a) Contrasting lithologies between background deposits and flood layers. Flood layers (grey bars) are characterized by the fine-grained top part of the layer ('clay cap') marked in light grey bars; (b) Grain-size measurements across one flood layer indicated by the white arrow in Lake Thun (core width = 6 cm) (modified from GILLI et al. 2013).

In addition to the occurrence and age of paleofloods, several studies indicated that paleoflood intensities can be reconstructed using lacustrine flood layers (BROWN et al. 2000; MULDER et al. 2003; BUSSMANN AND ANSELMETTI 2010). The thickness of a detrital layer reflects the volume of mobilized particles, whereas the grain-size distribution of the flood turbidites may reflect the flood dynamics and magnitude. However, these characteristics of the flood layers are also influenced by sediment availability in the catchment, which in turn is influenced by climate, human impact and vegetation cover.

2.3. Geoarchives and historical data from floodplains

2.3.1. Multi-archive analysis of floodplains

Most Pleistocene, glacier-scarped main valleys of the Alps are hotspots of flood risk in Switzerland. The principal reason is the dense population and very limited space for settlement, corresponding mostly to distal areas of alluvial cones and river floodplains, and the fast flood response of small- and mid-size Alpine catchments to heavy rainfall (WEINGARTNER et al. 2003; VISCHER 2003). The on-site analysis of flood archives on floodplains where major damage occurs is promising, but also challenging, due to the complexity of physical processes involved in a dynamic mountain environment (SCHULTE et al. 2019b). Nevertheless, the floodplains of Alpine main valleys and deltas in Switzerland provide excellent sites to reconstruct a continuous flood history (SCHULTE et al. 2009a; SCHULTE et al. 2015; LAIGRE et al. 2013). For example, fluvial erosion, aggradation, channel shifting and avulsion, crevasse splay, effects of embankment and channel correction, generated a characteristic spatial imprint of valley floor geomorphology over centuries in the Aare River valley **(Figure 2.1)**.

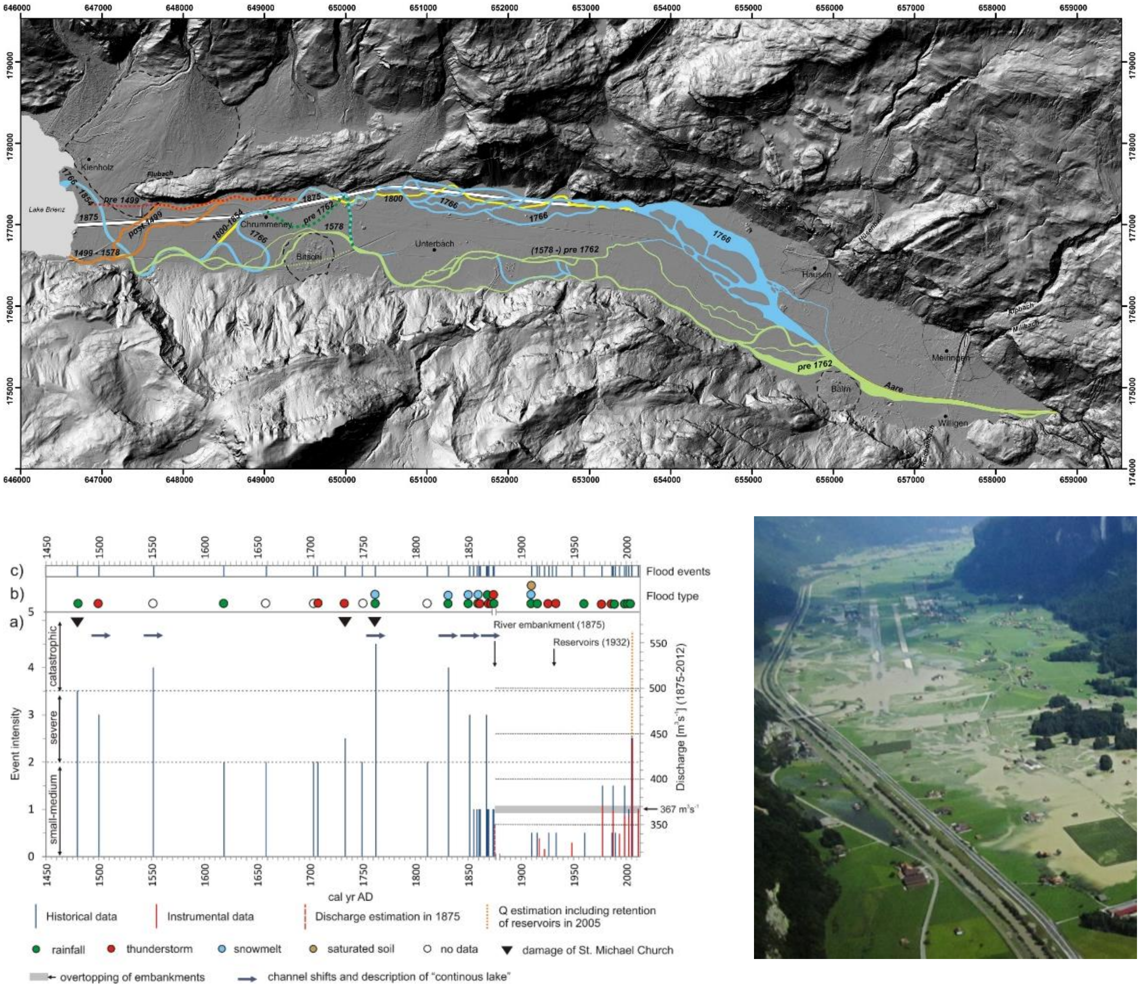

*Figure 2.1: Top -- Evolution of Aare River paleo-channels reconstructed from historical maps, field survey and documentary sources. Bottom left -- Historical flood chronology of the Aare river in the Hasli Valley from AD 1480 to 2012 (*SCHULTE et al. 2015*). Bottom right -- Oblique aerial photograph (Credits Schweizer Luftwaffe) of the 2005 flooding of the Hasli-Aare floodplain.*

The problem of complexity of the time-space evolution of floodplain dynamics can be overcome by an accurate multi-archive reconstruction as demonstrated by SCHULTE et al. (2009a), (2009b), (2015) for the Lütschine and Lombach Deltas and the lower Hasli-Aare Valley (**Figure 2.1**). From the integration of historical data, channel capacity and instrumental measurements, the authors concluded that before AD 1875 a discharge of 351 m^3s^{-1} (a conservative estimate) produced small-medium intensity damage, whereas a discharge of 500 m^3s^{-1} or higher, probably caused catastrophic damage.

2.3.2. Flood reconstruction from floodplain deposits

Sedimentary and geochemical proxy data can be obtained from floodplain deposits (SCHULTE et al., 2008; 2015; CARVALHO and SCHULTE, 2013; **Box 2.2**). These data can be used to reconstruct flood activity by tracing geochemical signatures in floodplain deposits (SMITH and BOARDMAN 1989; PAINE et al. 2002; SCHULTE et al. 2008; JONES et al. 2012; BERNER et al. 2012).

Box 2.2: Sedimentary floodplain archives

Different sediment structures, facies and mineralogy of flood layers result from colluvial, fluvial, alluvial and soil-formation processes. Channel and crevasse splay deposits are generally composed by coarse sand and gravel, levees by sand layers, and over-bank deposits by fine sand and silt, and interdistributary basins contain clay-rich and organic-rich layers as well as peat horizons (**Figure**). River channel shifts and avulsions may cause erosion and re-deposition, whereas sediments in intradistributary basins are deposited conformably. In addition, grain size also reflects flood magnitude. During larger floods, coarse-grained flood layers are deposited, while during moderate and minor floods, fine, sand and silt deposits, and organic-rich horizons are generally formed (SCHULTE et al. 2009a; BERNER et al. 2012).

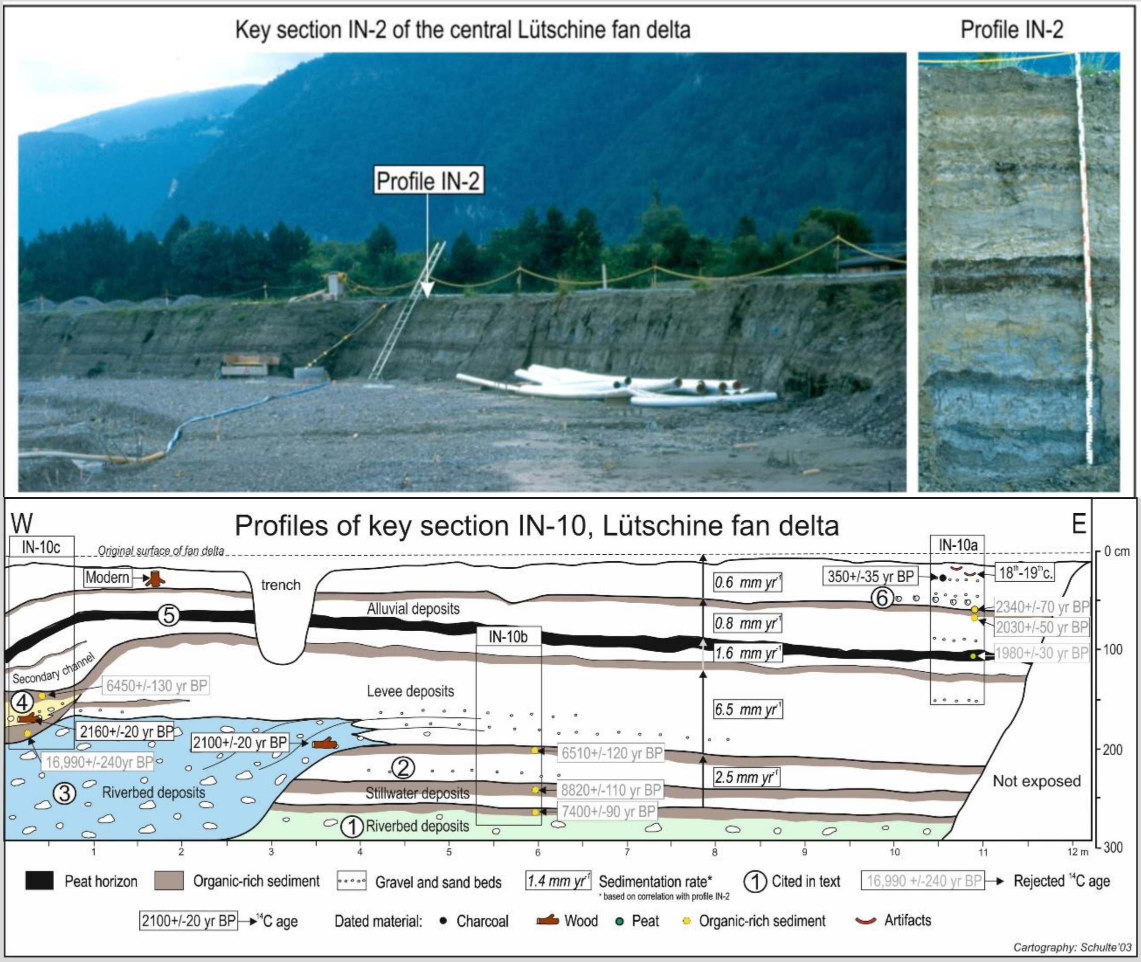

Figure: Top -- IN-2 key section of the Lütschine fan delta. Below -- Lithology, facies and chronology of the IN-10 key section, located 250 m southwest of the IN-2 section. Radiocarbon dates presented in grey were not used for the chronological model (modified from SCHULTE et al. 2009a*).*

BERNER et al. (2012) reconstructed the modern river flood history of the Rhine River based on the correlation between discharge and carbonate content of the suspended load of the Rhine River and floodplain chemostratigraphic characterization. SCHULTE et al. (2008), (2009), (2015) studied the provenance, deposition and diagenetic processes of sedimentary materials and pedological features in several floodplains of the Bernese Alps.

Figure 2.2 shows several major deposition pulses and geochemical variability of upward thinning sequences in a key-section of the Hasli-Aare floodplain. The aggradation of sandy overbank deposits during major flooding is accurately recorded by Zr/Ti, Sr/Ti and Ca/Ti peaks associated with coarse-grained flood layers. Between AD 1480 and AD 1875 (termination of the Aare River Correction) twelve of the fourteen historically recorded extreme events were also recorded by coarse-grained flood layers (**Figures 2.1 and 2.4**). Furthermore, the ratios of stable elements provide information on the provenance of sediments. Zircon is a tracer for sediment supply from the highest area of the basin because this heavy mineral is present in the crystalline rocks such as syenite, granite and amphibolites of late Palaeozoic intrusions.

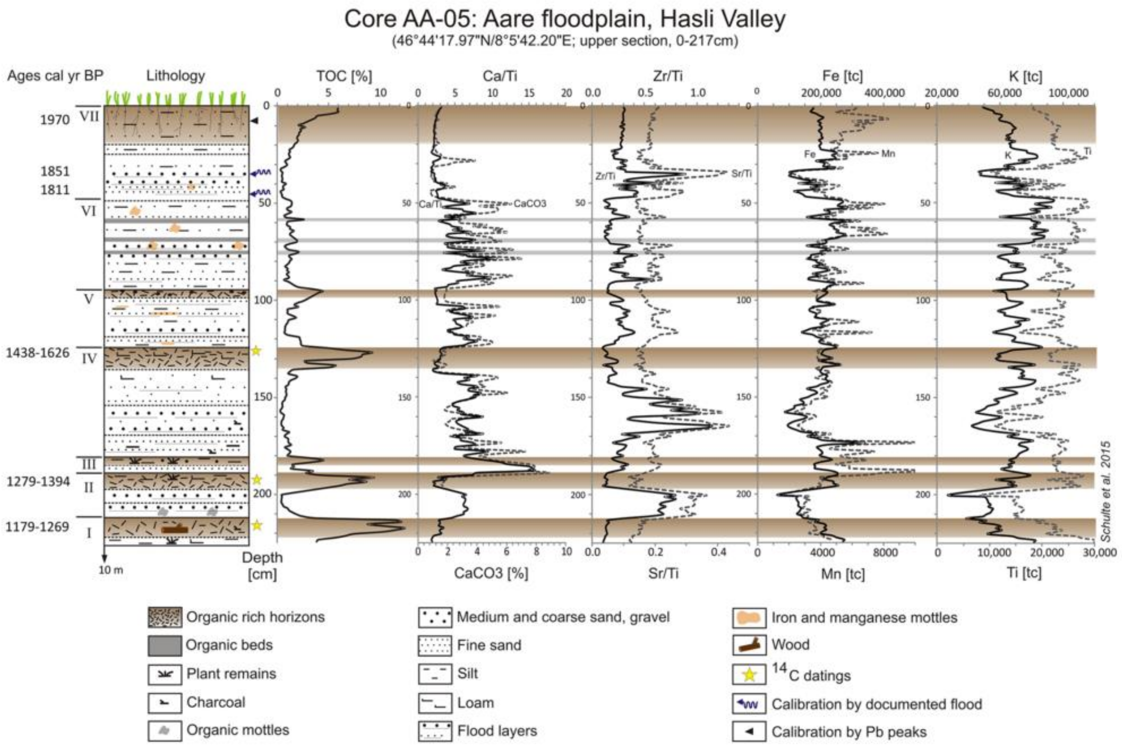

Figure 2.2: Lithology, chronology and geochemical stratigraphy of a core from the Aare floodplain. (from SCHULTE et al. 2015).

2.4. Paleoflood reconstructions based on tree rings

Trees preserve evidence of floods in their annual growth rings whenever they are impacted by floods. The use of trees as paleoflood indicators is based on the 'process–event–response' concept (SHRODER 1978), in which a flood represents the 'process', the 'event' is the resulting tree disturbance (e.g., abrasion scars, abnormal stem morphologies, eroded roots, tilted trunks, or standing dead trees) and the 'response' refers to the physiological response of trees to the disturbance, which results in a specific anatomical imprint created within the tree's annual growth rings (STOFFEL and CORONA 2014; BALLESTEROS-CÁNOVAS et al. 2015a). Scars on tree trunks are the most common evidence of past flood activity. Scars are caused by the impact and abrasion of debris and wood transported during floods (STOFFEL and BOLLSCHWEILER 2008). Scarring can also cause secondary growth and anatomical signatures, such as tangential rows of traumatic resin ducts, changes in vessel size, or callus tissues (BALLESTEROS et al. 2010; ARBELLAY et al. 2012). These features are used to identify the year of past floods, and sometimes even determine the season of flooding (STOFFEL and CORONA 2014). The height of scars can be used to derive peak discharge estimates (BALLESTEROS-CÁNOVAS et al. 2011).

Other paleoflood evidence recorded by trees include (**Figure 2.3**): (i) abrupt decreases in tree-ring widths due to partial tree burial, which limits their nutrient supply and ability to take in water (FRIEDMAN et al. 2005; KOGELNIG-MAYER et al. 2013); (ii) changes in root anatomy after exposure by bank erosion (MALIK 2006), or (iii) anatomical anomalies produced when trees are inundated for weeks during the early growing season (ST. GEORGE et al. 2002; WERTZ et al. 2013).

The use of tree-ring records as a surrogate of flood timing and magnitude has expanded substantially in recent time (ZIELONKA et al. 2008, THERRELL and BIALECKI 2015, BALLESTEROS-CÁNOVAS et al. 2017). A detailed review of paleoflood studies based on tree rings is given by BALLESTEROS-CÁNOVAS et al. (2015a).

The reliability of tree-based paleoflood estimates has been tested against historical and instrumental flood records. The accuracy of the approach depends in part on tree age (TICHAVSKÝ et al. 2017) and species (BALLESTEROS-CÁNOVAS et al. 2015b) . Because riparian trees can be damaged by other causes (e.g. human activities), trees must be selected carefully to minimize the influence of non-flood signals. Moreover, because flood damage can vary between neighbouring trees, samples must be taken from a sufficiently high number of trees to replicate the flood signals and develop reliable estimates of past flood events (BALLESTEROS-CÁNOVAs et al. 2015a; CORONA et al. 2012).

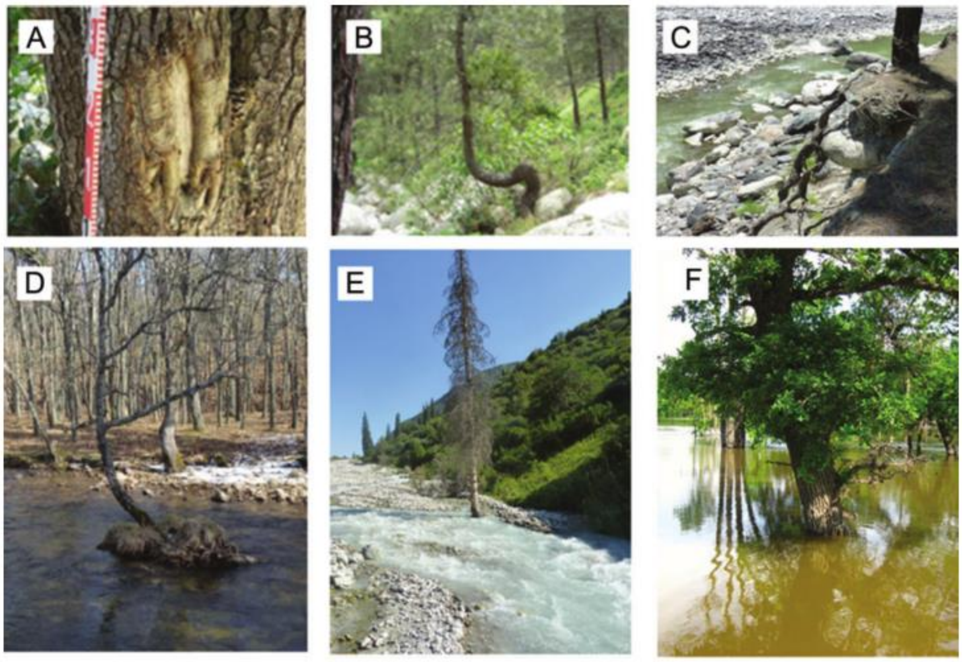

Figure 2.3: Types of botanical evidence to identify paleofloods using tree rings: (A) tree injuries; (B) broken stems and unusual stem morphologies; (C) exposed roots; (D) tilting trees; (E) dead trees; (F) abnormal anatomical structures due to inundation (from BALLESTEROS-CÁNOVAS et al. 2015a).

Tree rings have also been used to reconstruct mass-wasting processes in Switzerland, such as debris flows (STOFFEL and BOLLSCHWEILER 2008; SCHNEUWLY et al. 2012), landslides (SAVI et al. 2013; LOPEZ-SAEZ et al. 2017), rockfalls (STOFFEL et al. 2005; TRAPPMANN et al. 2013; MOREL et al. 2015) or snow avalanches (STOFFEL et al. 2006; FAVILLIER et al. 2017, 2018). To-date, tree-ring studies have not been applied widely to reconstruct floods in Switzerland.

2.5. Paleofloods and climate variability

2.5.1. Floods in the Northern Alps during the last 2500 years

A 2500-year long flood reconstruction for the Northern Alps, on the basis of dated sedimentary flood deposits from ten lakes in Switzerland, showed strong decadal to centennial-scale variations in the occurrence of floods (GLUR et al. 2013). The condensed signal on the basis of over 800 identified and dated flood layers is interpreted to be a regional paleoclimatic signal less influenced by local effects. These data were compared to an independent temperature reconstruction using tree rings sampled in an adjacent region (BÜNTGEN et al. 2011). The comparison indicates that high flood frequency coincides significantly with cool summer temperatures reflecting varying climate states through the last 2500 years affecting both temporal patterns of temperature and of precipitation extremes.

This pattern implies that enhanced (decreased) occurrence of westerly and Vb storm tracks during cooler (warmer) summers increase (decrease) the frequency of flood events in the Alps. As the main determining factor for the frequency of intense precipitation events in the Alps, a variable extent of the Hadley Cell and consequently changing atmospheric circulation patterns were proposed. This wet-cold synchronism suggests enhanced flood occurrence to be triggered by latitudinal shifts of Atlantic and Mediterranean storm tracks. This paleoclimatic perspective reveals natural analogues for varying climate conditions, and thus can contribute to a better understanding and improved projections of weather extremes and floods under climate change.

2.5.2. Holocene flood frequency across the Central Alps

Over 4700 flood layers from 15 lacustrine sediment records from the Northern and Southern Central Alps were identified, dated and merged in a comprehensive Alpine flood catalogue covering the past 10,000 years (WIRTH et al. 2013a). This Holocene flood record provides the possibility to investigate flood occurrence during warm (e.g. Holocene Thermal Maximum) and cool (e.g. Neoglaciation) periods at a large spatial extent, potentially providing information on characteristic atmospheric circulation patterns during different climatic conditions (**Figure 2.4**). At this large temporal and spatial scale, flood frequency was found to be higher during cool periods, coinciding with lows in solar activity. Periodicities of flood occurrence match those from reconstructions of solar activity from ^{14}C and ^{10}Be records. As mentioned above, the likely driving mechanism, an expansion/shrinking of the Hadley cell with increasing/decreasing air temperature, causing dry/wet conditions in Central Europe during phases of high/low solar activity is suggested. Furthermore, differences between the flood patterns from the Northern Alps and the Southern Alps indicate changes in North Atlantic circulation. Enhanced flood occurrence in the South compared to the North suggests a pronounced southward position of the Westerlies and/or blocking over the northern North Atlantic, hence resembling a negative NAO state (most distinct from 4.2 to 2.4 kyr BP and during the Little Ice Age). South-Alpine flood activity therefore provides a qualitative record of variations in a paleo-NAO pattern during the Holocene.

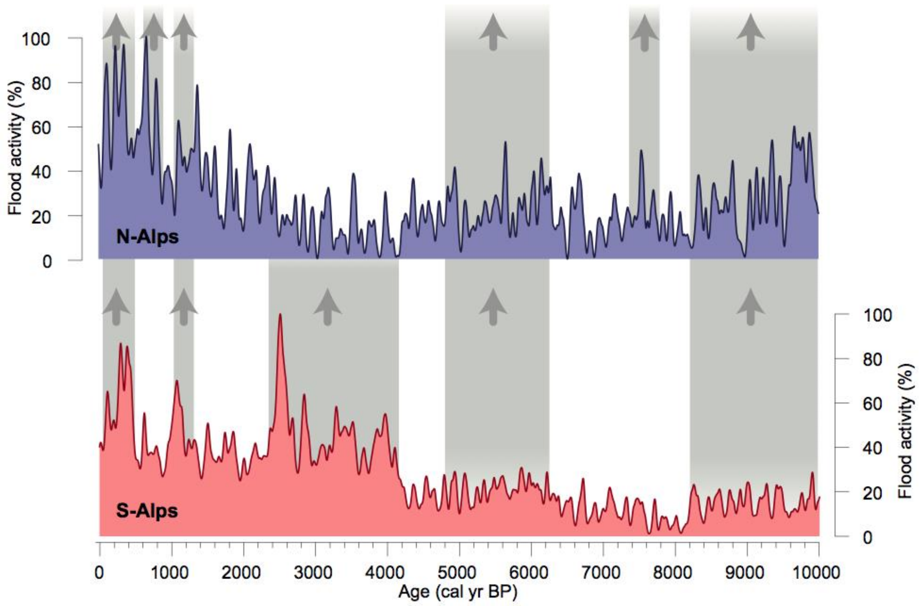

Figure 2.4: Stacked flood records for the N- and S-Alps (100-year low-pass filtered) spanning the past 10 kyr. Grey areas and grey arrows mark periods with increased flood activity (from WIRTH et al. 2013a).

2.5.3 2600-yr sedimentary flood record from the Hasli-Area floodplain

In the Bernese Alps SCHULTE et al. (2008), (2009), (2015) showed the possibility to correlate geochemical floodplain proxies with paleoclimate variability over three millennia. **Figure 2.5** shows that seven paleoflood clusters defined by flood layers deposited predominantly during periods of reduced solar irradiance, cooler summer temperatures and phases of drier spring climate. Cooler climate pulses typically generate glacier advance, more extensive snow cover, and snow patches through the summer. Water storage and larger areas susceptible for melting processes associated with rainfall episodes and abrupt rises in temperature can increase surface runoff on slopes and consequently the discharges of Alpine rivers. However, three flood clusters occurred during warmer climate pulses (1380-1420; around 1760; 1977-present). Glacier and snow melt, higher snow limits, reduced snow cover and consequently a larger area of surface runoff combined with intense summer precipitation promoted flooding in the valley floor in these periods.

Spectral analysis of the geochemical and pollen time series and climate proxies such as Total Solar Irradiance and $\delta^{18}O$ isotopes from Greenland ice cores, temperature and precipitation reconstruction from tree-rings, and climate teleconnection indices (NAO, SNAO), indicate similar periodicities around 80, 100, 120 and 200 years (Gleissberg and Suess cycles). Thus, the mechanisms of the flood processes, at this large scale, are influenced not just by local factors but are strongly influenced by the North Atlantic dynamics and solar forcing.

The influence of atmospheric circulation dynamics on flood frequencies in the Hasli-Aare Valley is observed when flood intensities and geochemical proxies from the Hasli Valley and indices of atmospheric modes AD 1670 to 2000 are compared (**Figure 2.5**; SCHULTE et al. 2015; PEÑA et al. 2015). Severe floods occurred mostly during positive trends of Summer North Atlantic Oscillation (SNAO) phases or short positive SNAO pulses (cyclones of Mediterranean origin) following years or even decades dominated by negative SNAO (North Atlantic front systems; PEÑA et al. 2015; PEÑA and SCHULTE, 2020). This combination underlines the importance of the effect of snowmelt during short warm episodes within cool climate periods characterized by larger snow cover and glaciers.

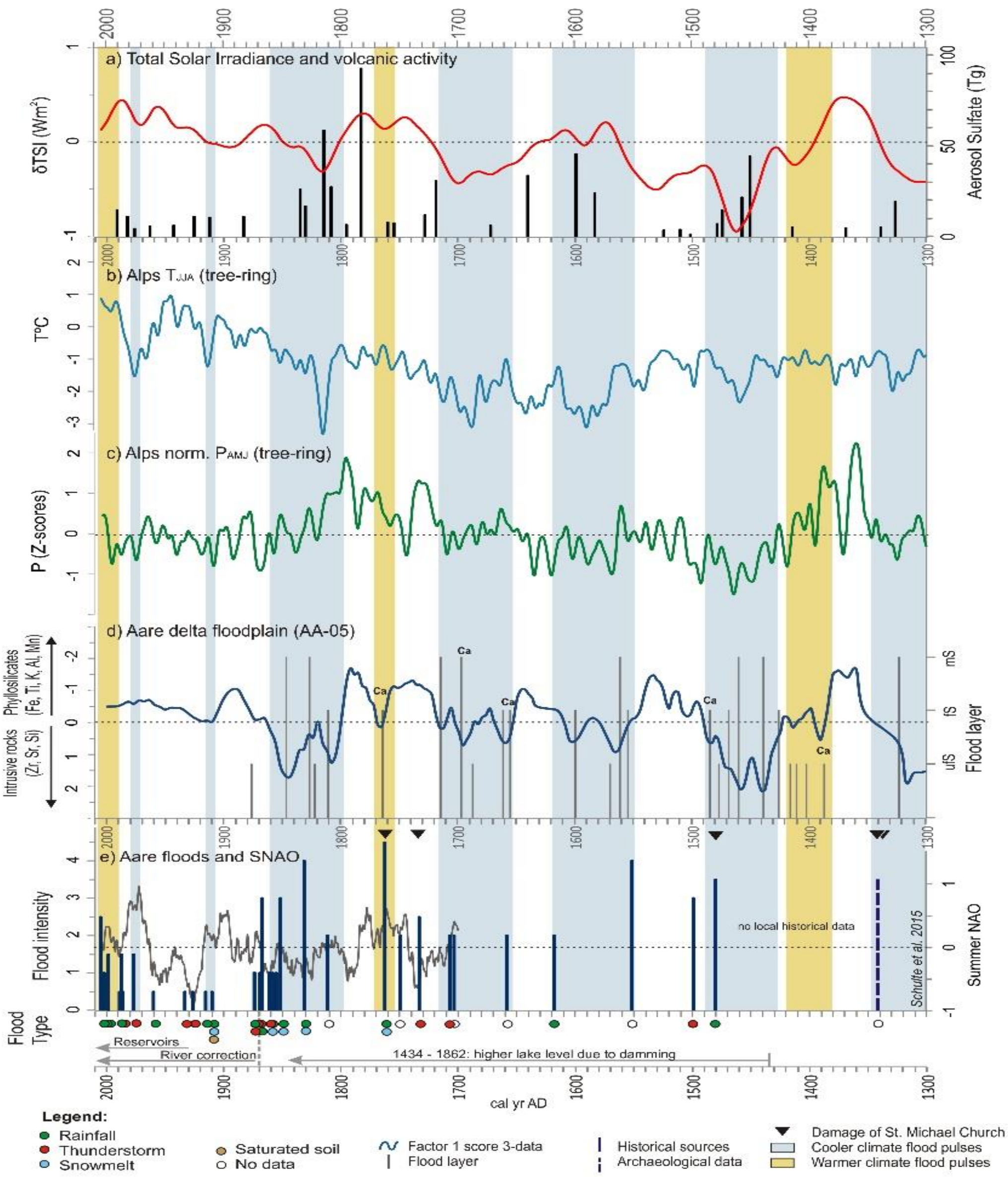

Figure 2.5: Comparison between historical flood reconstruction of the Hasli-Aare and solar and volcanic activity, tree-rings and climate proxies (1300-2010 cal yr AD) (from SCHULTE et al. 2015).

2.5.4 Temporal-spatial integration of multi-archive datasets in the Bernese Alps

The spatial and temporal integration of multi-archive flood series from the Hasli-Aare, Lütschine, Kander, Simme, Lombach, and Eistlenbach catchments constitutes an innovative approach to the reconstruction of accurate flood pulses over the last six centuries and the development of a temporal-spatial model of past flood behaviour (SCHULTE et al. 2019a, 2019b). Paleoflood records obtained from floodplains (four flood series) and lake sediments (four series), together with documentary data (six series), were analyzed and compared with instrumental measurements (four series) and the profiles of lichenometric-dated flood heights (four series).

The most accurate, continuous series, corresponding to the period from 1400 to 2005 CE, were integrated employing a complex integration process that involved data selection, normalization, filtering and factor analysis with different settings into a synthetic flood master curve that defines ten dominant flood pulses. This robust master curve improved the previously published individual floodplain and lake paleoflood data series. It is worth to note that the pulses of sedimentary floodplain proxies are similar to the flood evidences provided in documentary data series, showing the large flooding in the settled floodplains and deltas, whereas lake records from small catchments reflect more erosion processes related to hydro-meteorological events. Six of the integrated flood pulses correspond to cooler climate pulses (around 1480, 1570, 1760, 1830, 1850 and 1870 CE), three to intermediate temperatures (around 1410, 1650 and 1710 CE), while the most recent corresponds to the current pulse of Global Warming (2005 CE). Furthermore, five coincide with the positive mode of the Summer North Atlantic Oscillation, characterized by a strong blocking anticyclone between the Scandinavia Peninsula and Great Britain.

For two of the most catastrophic flood events in the Bernese Alps (those of 1762 and 1831 CE), the location and magnitude of all the flood records compiled were plotted to provide an accurate mapping of the spatial pattern of flooding. This was then compared to the pattern of atmospheric variability by applying CESM-LME simulations (SCHULTE et al. 2019b; PEÑA and SCHULTE, 2020). The event-related spatial information including low and high altitudes of flood evidence and the simulation of composite sea level pressure maps give a deeper insight in flood dynamics and forcing.

Take-Home Messages

- Reconstructions of paleoflood occurrence (and magnitude) are possible from sediment deposits in lakes and floodplains where sediments record floods, which together with sediment geochemistry and grain-size distributions, provide indications of flood magnitude and timing.
- Paleoflood reconstructions for shorter time periods can also be achieved by dendrochronology and lichenometry, which record a range of flood damages in the tree rings of riparian species and heights of flood levels by lichen colonization. Such paleoflood reconstructions are useful to fill gaps in instrumental records, extend time series of floods, and provide envelopes on extremes.
- Data show a connection between long-term climate variability and floods at a regional scale, where evidence of large-scale shifts in weather pattern and long-term climatic oscillations lead to the clustering of floods into flood-rich and flood-poor periods. The analysis of the paleoflood records provides insights into how future climatic variations might influence flood magnitude and frequency.
- Centennial to millennial-scale fluctuations in flood activity are governed by periodicities in climatic mechanisms and forcing factors. Variations in solar activity are an important factor in climate variability as well. For example, high flood activity correlates to low solar activity, Holocene cold events, and to global/Alpine glacier advances.
- Human activities such as deforestation and agriculture, especially in the northern part of the Alps, could have resulted in the increasing trend in flood activity during the past 2-2.5 kyr on top of climate forcing. River regulation and reservoirs mask the climate signal of floods since the 19th century.
- A new integrative approach developed and tested in the Bernese Alps provides a comprehensive 4-D picture of paleofloods which facilitates an in-depth understanding of floods and flood forcing in mountain catchments.